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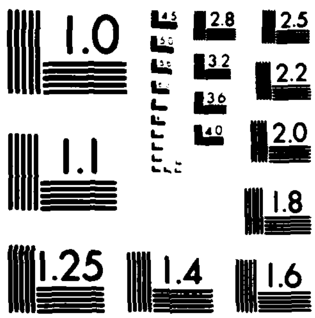

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THE HIGH ZENITH ANGLE LIMITS OF COSMIC RAY ACCESS TO AN EARTH SATELLITE

David J. Cooke

The University of Utah
Salt Lake City, Utah 84112

Scientific Report No. 4

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The question of the high zenith angle limits pertaining to access of charged cosmic ray particles of any given rigidity to an earth satellite is an important one to investigators who rely on the presence of the solid earth and atmosphere to screen a satellite from upwards moving particles.

The trajectory parameterization method has been used to elucidate the general characteristics of the different kinds of solid angle region that cont

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) cont. can be distinguished relative to a satellite (or more generally to any given point within the geomagnetic field). These regions are: those into which particles may be allowed, those into which particles are forbidden because of the local blocking effect of the earth and atmosphere, and those regions into which charged particles may have access via means of long bound or quasi bound periodic trajectories.

This report presents some of the phenomenology associated with these regions, and discusses aspects of their latitude, longitude, zenith, azimuth and rigidity dependence.

THE HIGH ZENITH ANGLE LIMITS OF COSMIC RAY ACCESS TO AN EARTH SATELLITE

David J. Cooke
Department of Physics
University of Utah
Salt Lake City, Utah 84112

Introduction

A knowledge is often required of the highest zenith angle for which a charged particle of given rigidity has access to an earth satellite lying in a particular orbital configuration.

Because of the complexities of the trajectories by which below-line-of sight access to a satellite occurs it has proven difficult to determine systematically whether absolute limits exist beyond which access is forbidden. The general approach to this problem has been to directly test for access by carrying out a large volume of trajectory traces. This method, however, is not completely satisfactory because the absence of detected access beyond a given given angle does not constitute a satisfactory proof that access could not occur (either via undetected allowed tractories that exist under the geomagnetic field conditions simulated, or under even slight perturbations away from these conditions).

A technique has been developed, based on the trajectory parameterization method (Cooke, 1982), which allows a very much more definitive insight into the problem of establishing the high zenith angle limits.

Discussion

The new method involves the examination of the form of trajectories along which particles approach a satellite, and consideration of whether these orbits can or cannot provide access for charged particles entering from outside the geomagnetic field. (In line with ordinary trajectory tracing practice the traces are carried out in the reverse, negative-time, direction - out away from the satellite.)

Before discussing the technique further it is appropriate to briefly review the question of access to a point in an axially symmetric representation of the geomagnetic field (as investigated by Stormer (1930, 1955), and by Lemaitre and Vallarta (1936a, 1936b). In a simple, axially symmetric field, three types of solid angle regions may be distinguished relative to any point in the field:

a) The "main cone" - the region into which access is directly allowed via simple aperiodic trajectories,

b) The "Stormer cone" - into which access is forbidden to particles from outside the field, In this region trajectories passing through the given point have the form of bound periodic orbits.

c) The "penumbra" - the solid angle region lying between the main and Stormer cones, into which access is neither expressly allowed nor forbidden by the theories of Stormer, and Lemaitre and Vallarta. The region typically consists of admixed allowed and forbidden subregions.

In the real field (non axially symmetric) the situation is complicated by the fact that the Stormer cone is very difficult to define, because the associated trajectory forms do not correspond to perfect bound periodic orbits. It has been difficult to determine the properties of the quasi bound periodic orbits, and to decide whether access from outside the field could occur along such trajectories. This problem has in part been addressed in the present study, and satisfactory working principles have been developed for dealing with the question of possible access.

For the purpose of this investigation it has proved practical and useful to distinguish four different kinds of solid angle regions relative to a given point in the "real" field. These are the regions within which:

(i) access is forbidden because of short range intersection with the atmosphere (as detected in the outwards trajectory trace). These trajectories correspond to the short range "shadow" orbits of Lamaitre and Vallarta.

(ii) access from outside the geomagnetic field either does or could possibly occur along aperiodic or unstable quasi-periodic orbits.

(iii) entry would only be by aperiodic or quasi-periodic orbits that intersect the surface of the earth.

(iv) approach could occur via quasi-periodic orbits that have no detected intersection with the atmosphere. Such trajectories can extend for very large distances in the field without any detected field escape or earth intersection. It is impractical (or even sometimes impossible) to trace these to some definite end, so the traces are terminated at a nominated path length. Thus the matter of access via such trajectories remains unresolved (the question of the precision of very long trajectory traces necessarily enters here, but will not be discussed).

Figures 1 through 4 illustrate trajectories associated with the four kinds of region. In the trajectory parameterization technique used in this study (in which trajectory features are "recognized" by computer, and their positions monitored for use in, for example, mapping cut-off structures, and establishing penumbral structure detail), it is important to continue the trajectory traces on beyond the first earth intersection. This is an artifact necessary to the operation of the technique (and in the identification of trajectory form), and is not held to represent any kind of reality. Thus, in Figures 1 and 3, the trajectories are seen to pass through the surface of the solid earth (where the location of the surface is represented by the dashed line).

Preliminary investigations have been carried out, using the trajectory parameterization technique, to elucidate the form and properties of the regions containing the trajectories of the four kinds. As a first step in this study, the regions containing trajectories of type (iv) are mapped, either in zenith-azimuth, or in latitude-longitude, space. An example of zenith-azimuth mapping is given by Cooke (1982), and reproduced in part as Fig. 5. The high zenith angle limits are set by the structure visible in the west at ~145° zenith angle. This boundary is formed by short range shadow orbits.

When mapped in latitude and longitude the regions typically have the form shown in Figure 6. At the given zenith and azimuth (150° and 270° respectively) access by positively charged 7 GeV particles to a satellite in a 400 km geocentric orbit is explicitly forbidden at all points on the earth's surface shown by the hatching. The boundary of the central region (within which access is not explicitly forbidden as a result of 1st and 2nd loop earth intersections) is in part formed by the edge of the region associated with 1st loop intersections, and in part by the edge of the region associated with the 2nd loop intersections. As rigidity varies the region defined by the 1st order shadow orbits changes shape as shown in Fig. 7. The 2nd order shadow limits are more stable, and change very little over this rigidity range. A change in zenith typically produces the shift shown in Fig. 8, and change in azimuth the shift to the positions shown in Fig. 9 and 10.

The Band Shift Factor (Cooke, 1982) can be used to quantitatively express the stability of these structures (see Table 1). It is interesting to note the relatively great stability of the central second order structure, which lies along the geomagnetic equator.

Table 1. Band Stability Factor $\partial R/\partial P$, where R is rigidity, and P is the the parameter in question, for the points, A, B and C in Figure 6. Large BSF values are associated with relatively stable structures.

	LAT	LON	ZE	AZ	ALT	GRAZ
A	-0.595	-0.043	-0.174	-0.054	0.015	-0.018
B	-0.750	-0.030	0.236	-0.247	-0.014	0.013
C	0.109	-0.004	-0.245	0.032	0.019	-0.023

By examination of the form and position of the shadow orbit defined regions it is possible to discount the possibility of high zenith angle entry at azimuths well away from the west, and to rigidities less than a given value (which value depends on the zenith angle considered, e.g. entry is forbidden for rigidity > 9 GV at zenith angle of 150°).

Within the central region exist fine allowed-forbidden structures associated with 3rd, 4th, and so on, loop intersections. The mapping of these structures has been found impractical because of the large amount of computer time required. In any case the detailed form of the structures depend significantly on the choice of geomagnetic field model used in the calculations (whereas the structures associated with 1st and 2nd loop intersections are relatively stable). It is therefore necessary to use some other means of determining what access is possible into this region.

Examination of the form of the trajectories associated with approach to points within the central region allows the question of access from points outside the geomagnetic field to be pursued, and permits general conclusions to be drawn about whether access is possible or impossible in given situations. This examination has been done by means of sets of trajectory traces applying to directions spaced in latitude and longitude (typically at 5° intervals in latitude, and 30° in longitude). The trajectories are displayed on a video terminal and visually categorized into types (ii), (iii), or (iv). Generally type (iii) and (iv) orbits are readily distinguished, although there is a less distinct difference between type (iii) and type (ii) orbits. The question arises of when short range quasi-periodicity turns into a regular periodicity. Not withstanding this point, meaningful boundaries can be established. Figure 8 shows the location of the boundaries for this set of conditions.

In general it is found that trajectories originating close to the geomagnetic equator show the most simple and regular periodicity (see Figs. 3 and 4). Further away to either side the trajectories become more complex in their periodic form, and further away again degenerate into unstable quasi-periodic or aperiodic forms (see Fig. 2), along which access may occur from outside the field (the short range shadow structures tend to be responsible for preventing access along what otherwise may be allowed trajectories). It is possible to anticipate whether trajectories of type (ii) occur before the shadow edges close off access, and it is therefore found unnecessary to actually locate an allowed trajectory in order to anticipate possible access via trajectories of this type.

The offset of the earth's dipole gives rise to a strong longitudinal asymmetry in the form of the regions (see Fig. 7 for example). There is a strong tendency for type (iv) trajectories to be normally associated with access to points at longitudes close to 300°, whereas type (iii) predominate over the rest of the longitude range. Because the 1st order shadow patterns are mainly (for the boundary conditions of interest) centered within the range 90-180° longitude, these regions can be regarded as being populated largely by type (iii) trajectories, with type (ii) orbits (if they occur at all in a given situation) lying at points removed from the geomagnetic equator.

In general, as rigidity decreases the size of the mapped regions increase. At the same time, however, the trajectory configurations evolve into a much more tightly bound periodic form, of types (iii) and (iv). Particles could conceivably populate such trajectories--possibly primary cosmic rays under time varying field conditions, or splash albedo particles, for example.

Conclusion

In extending this preliminary investigation it will be necessary to make an examination of the zenith, azimuth, rigidity, and altitude dependence of of the mapped regions. In this way a more complete picture could be drawn up of the zenith angle limits of access - limits to the regions containing trajectories associated with access of the kinds possible and impossible, probable and improbable.

Acknowledgments

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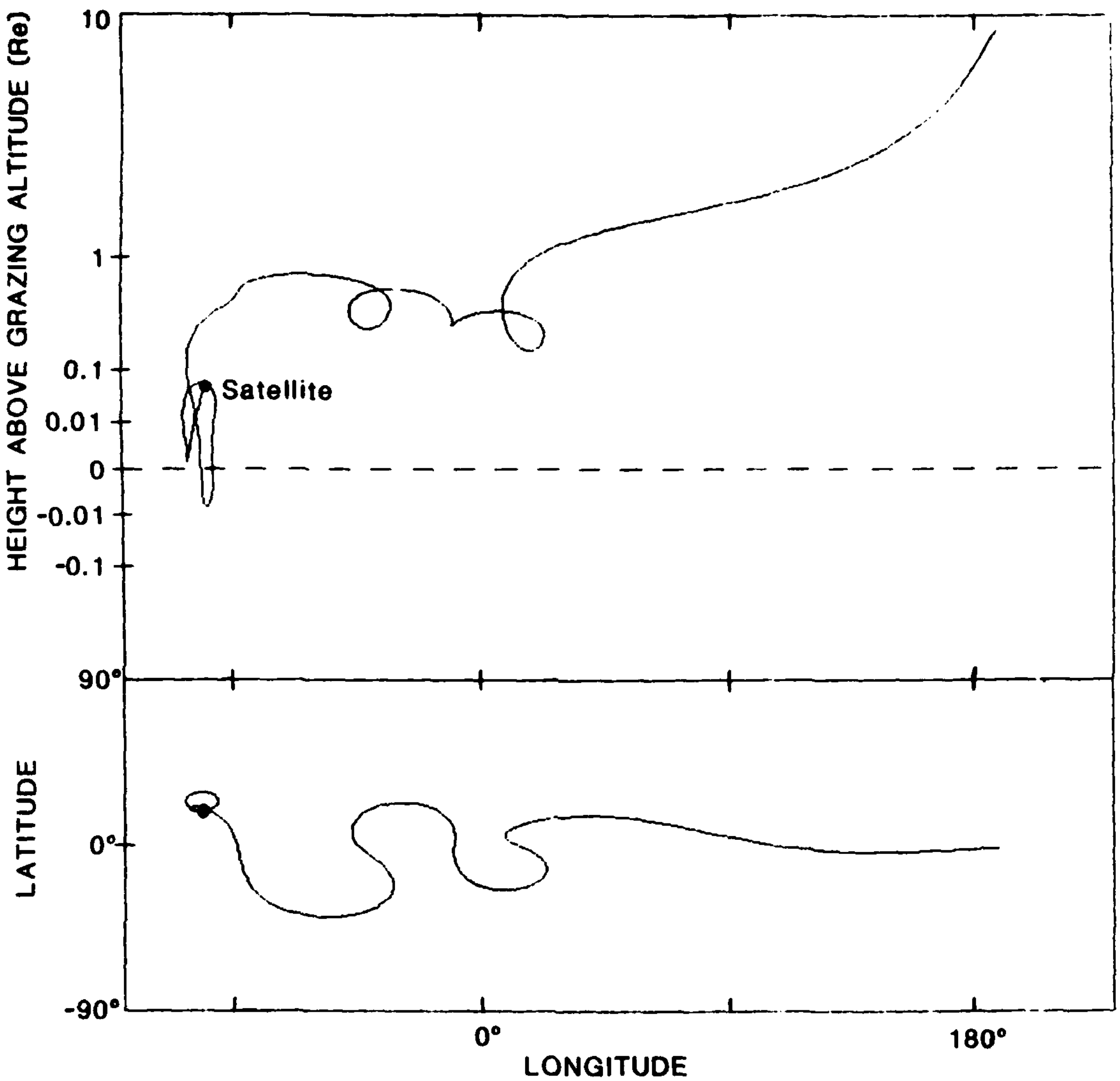

Figure 1. Trajectory (type (i)) displaying short range "shadow" intersection with atmosphere. The trajectory, which was continued on past the intersection, indicated that escape from field (or entry from outside the field) would otherwise have been possible. [Trajectory arrival point parameters lat. = 17.5°N., long.= 260° E, Ze = 145°, Az = 270°, Rig. = 7.5 GV, Alt. = 400 km; Grazing = 30km; geomagnetic field IGRF80].

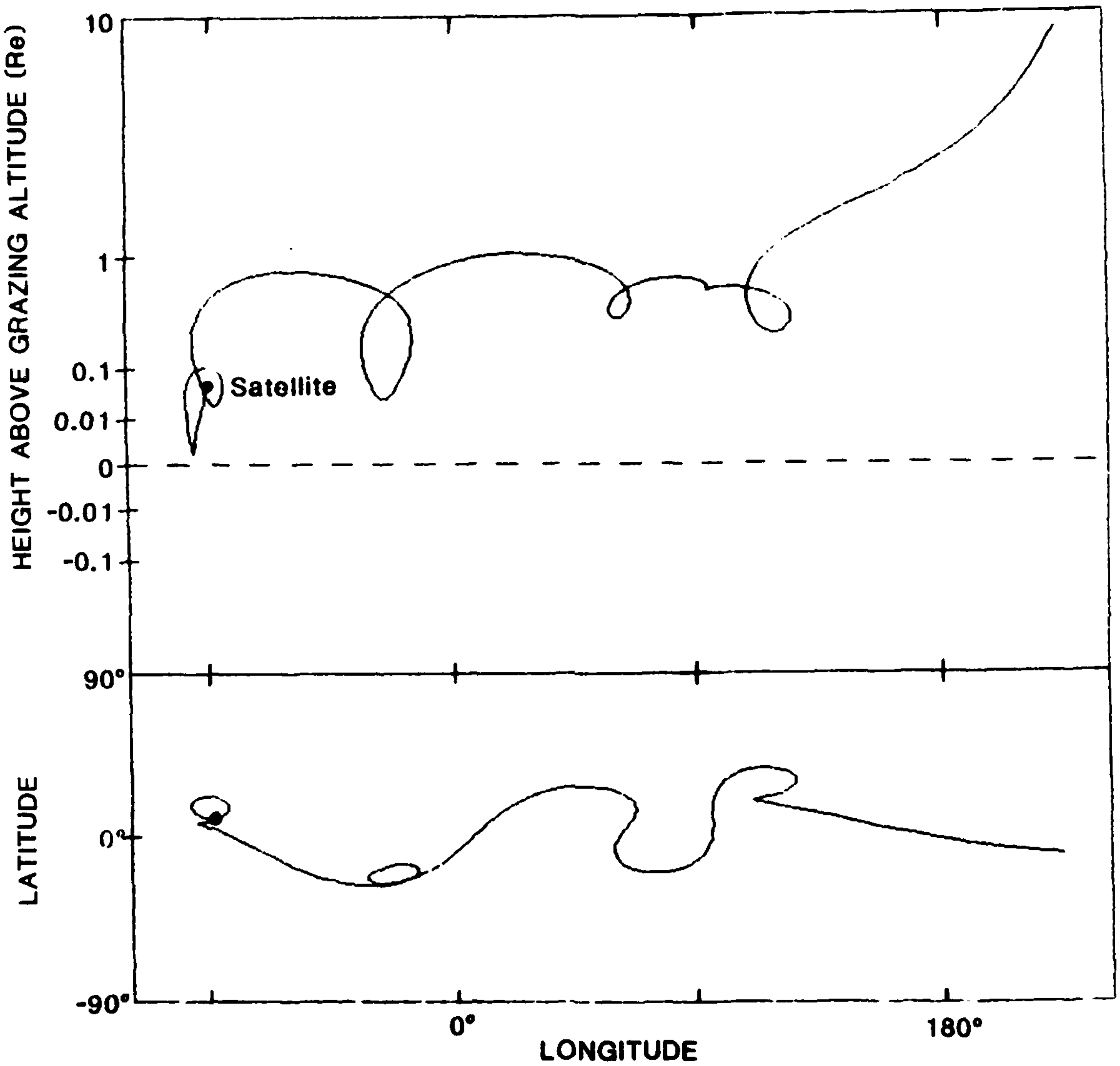

Figure 2. Trajectory of type (ii) - along which point in field is accessible via aperiodic orbit.
[Trajectory parameters lat. = 10, long. = 270, Ze = 144.5, Az = 278, Rig. = 7.7, Alt. = 400, Grazing = 30; geomagnetic field IGRF80].

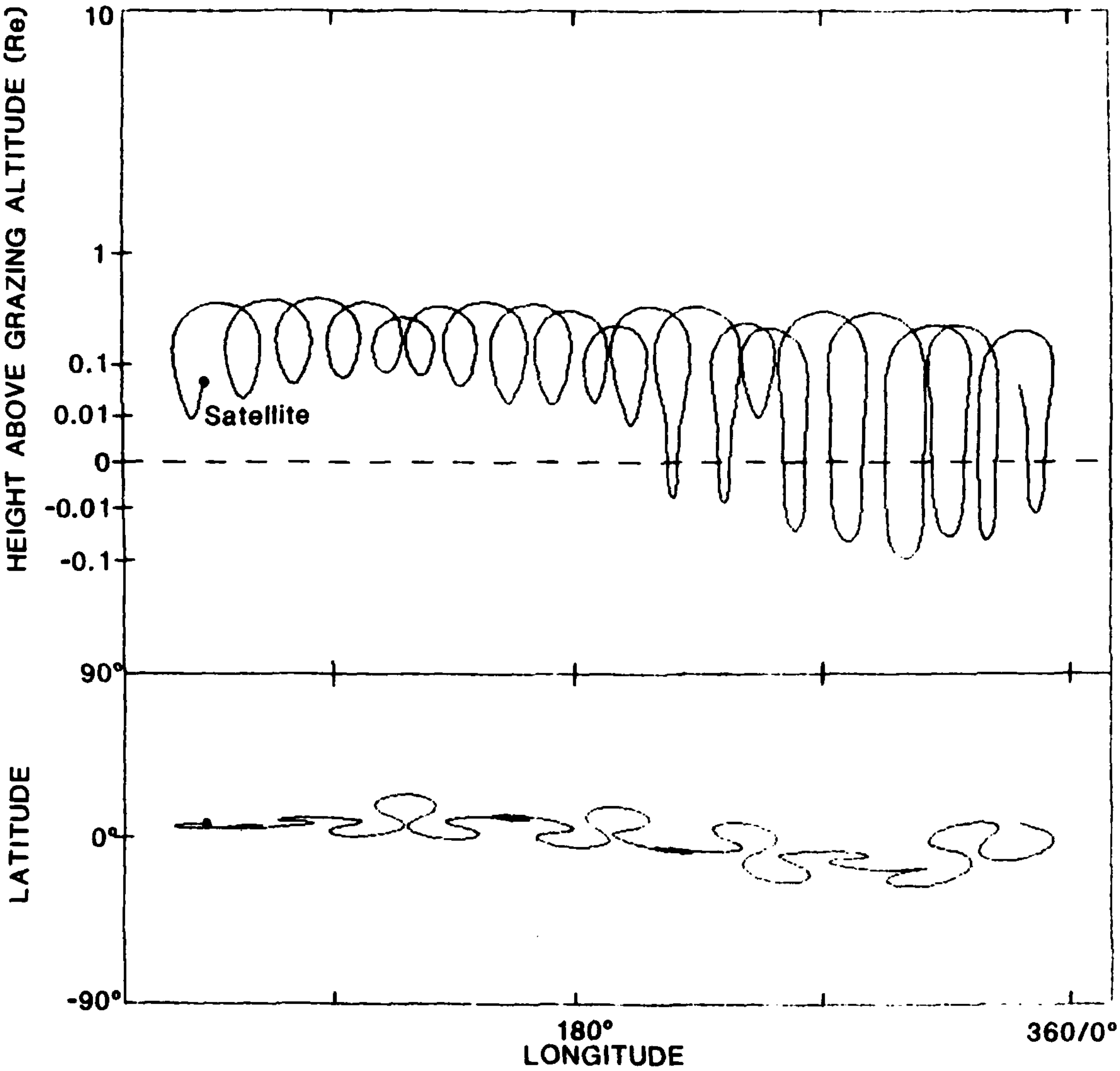

Figure 3. Type (iii) trajectory - showing regular quasi-bound periodic form, intersecting the atmosphere.
[Trajectory parameters lat. 7.5, long. = 45, Ze = 145, Az = 270, Rig. = 7.5, Alt. = 400, Grazing = 30; geomagnetic field IGRF80].

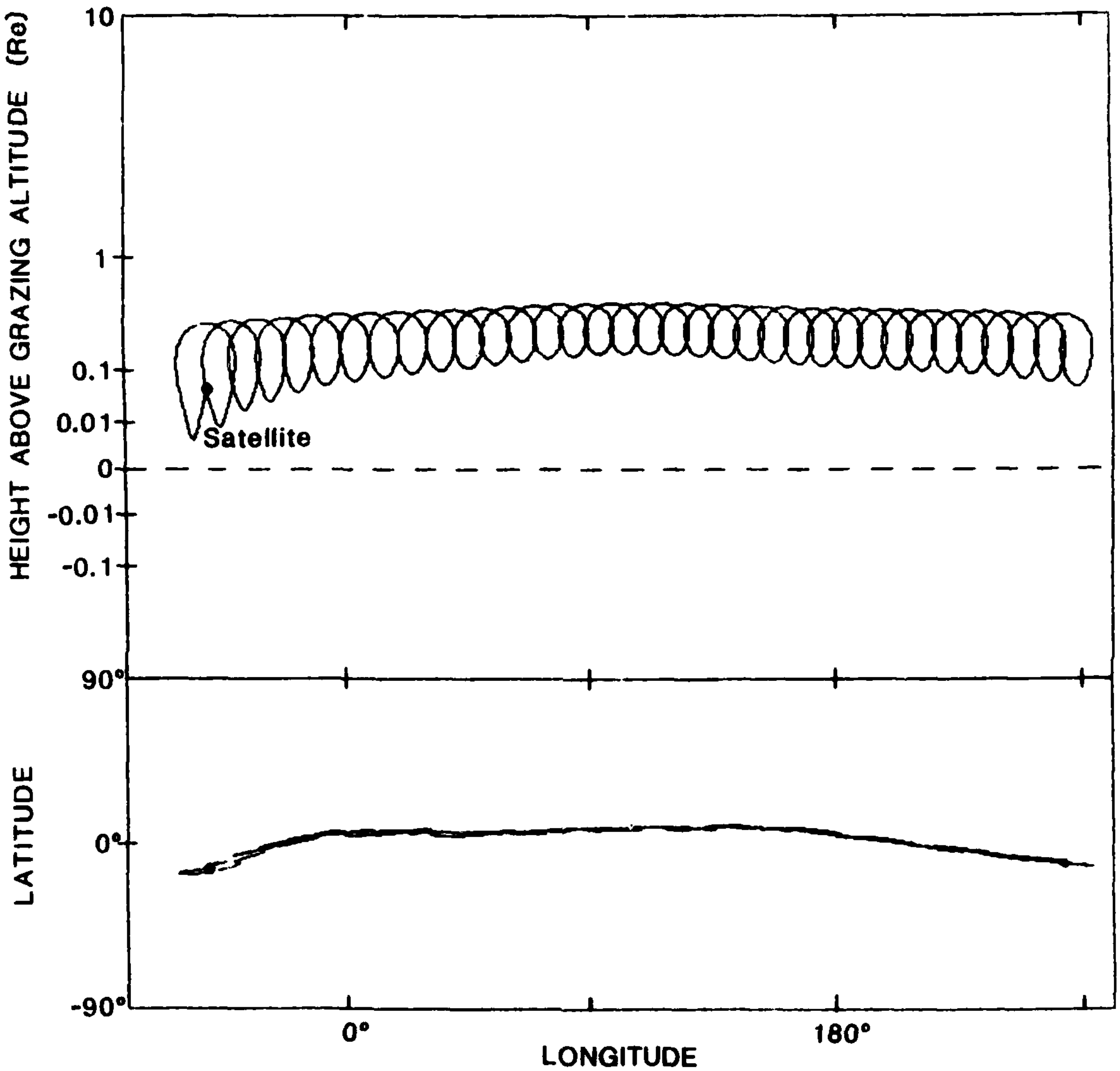

Figure 4. Trajectory of type (iv) - bound periodic form with no detected intersection (in this particular case, no detectable intersection, as the trajectory was found to stay clear of the atmosphere at all longitudes).
[Trajectory parameters lat. - 13.5, long. = 310, Ze = 270, Az = 5, Rig. = 400, Alt. = 400, Grazing = 30; geomagnetic field IGRF80].

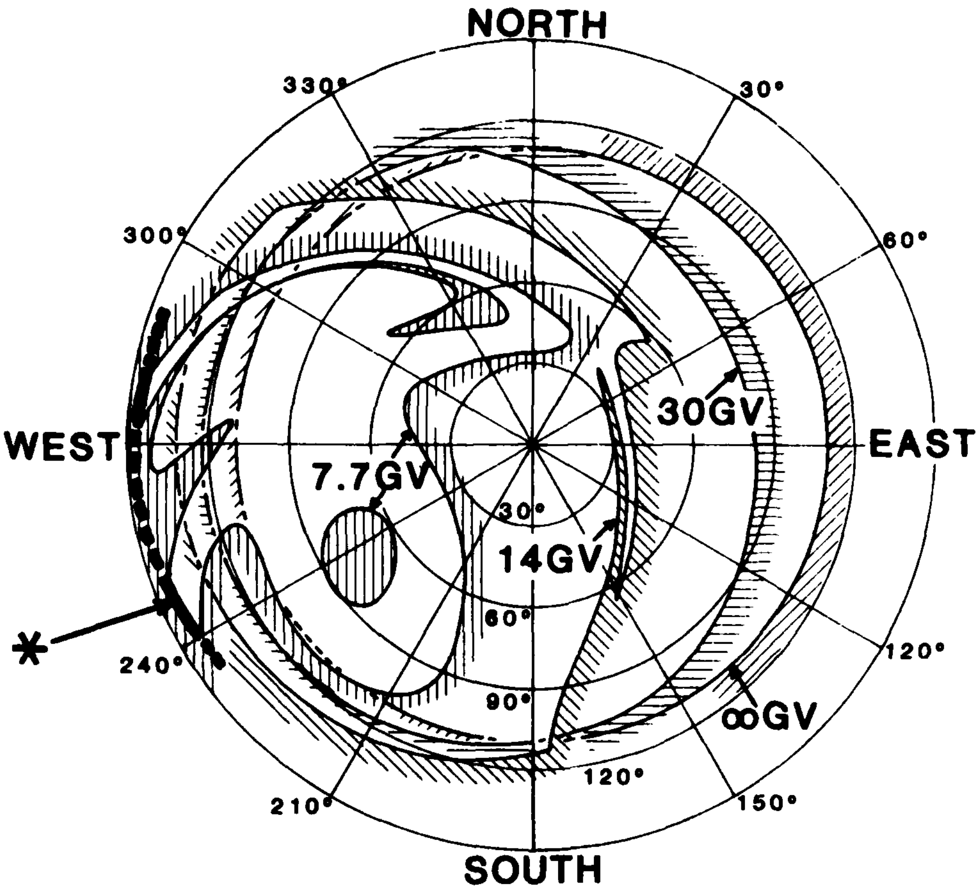

Figure 5. Position of allowed and forbidden structures mapped in zenith and azimuth for the indicated rigidity values, at the point 10° N latitude, 270° E longitude (IGRF80 field). The shadow structure limiting the high zenith angle entry in the west, for the 7.7 GV rigidity value, is indicated by an asterisk(*).

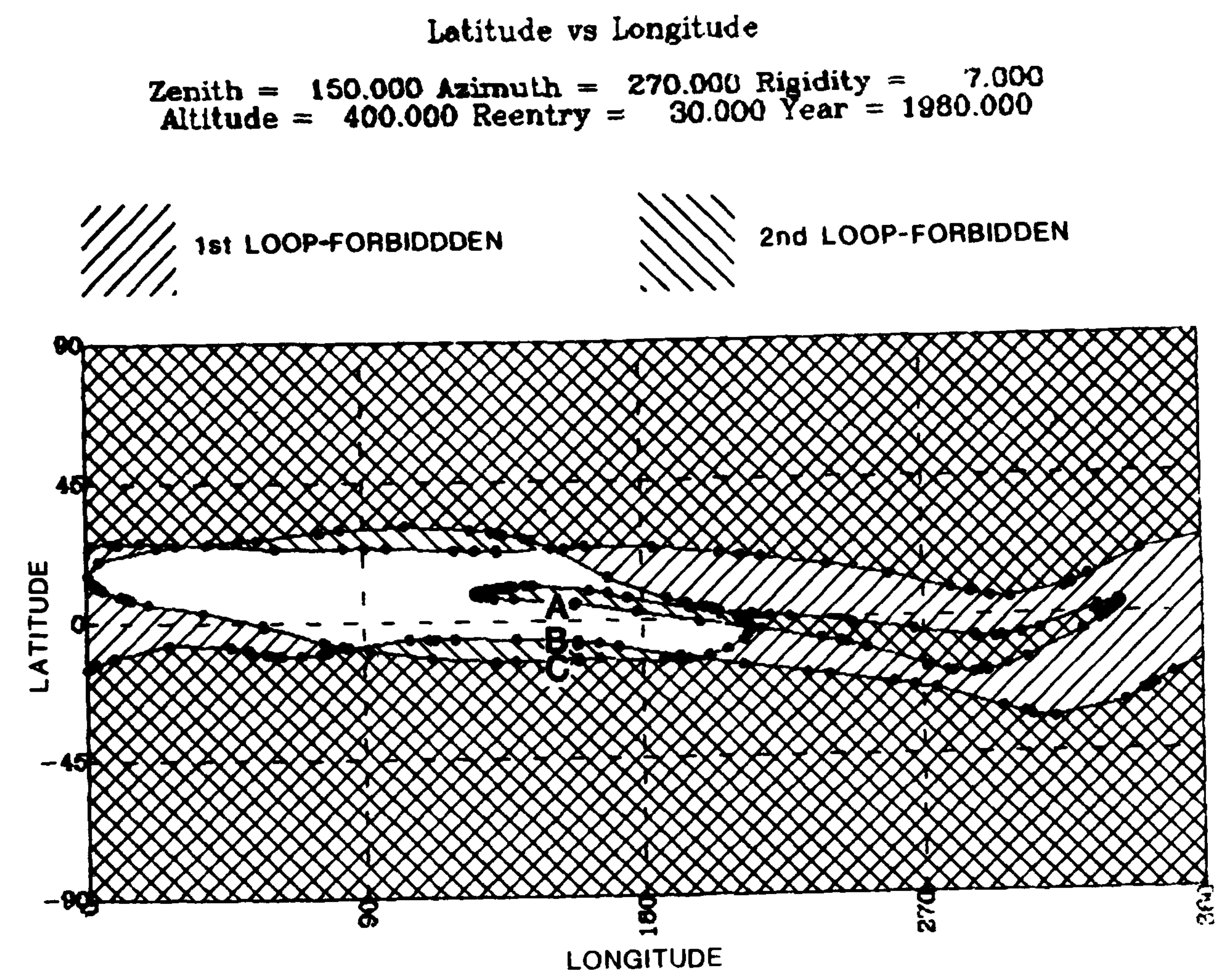

Figure 6. Latitude-longitude map showing zones of access under the indicated conditions. The Band Shift Factors have been calculated for points A, B, & C, and are presented in Table 1. The shaded region is inaccessible due to intersection of 1st and/or 2nd loops with the atmosphere and solid earth.

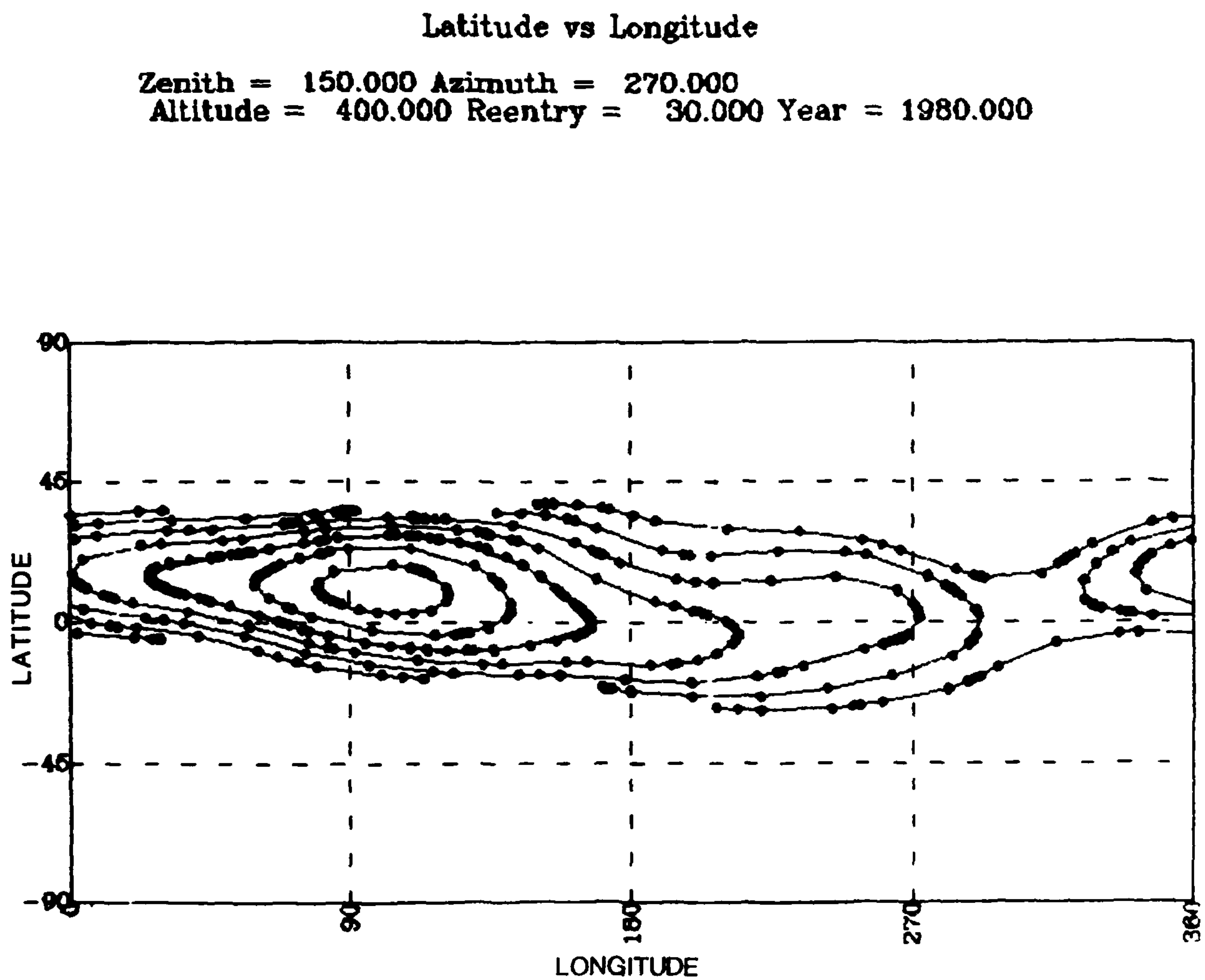

Figure 7. Position of the first order shadow edge for 8.5, 8.0, 7.5, 6.5, 6.0, and 5.5 GV (8.5 GV is the innermost, smallest, region), under the stated conditions.

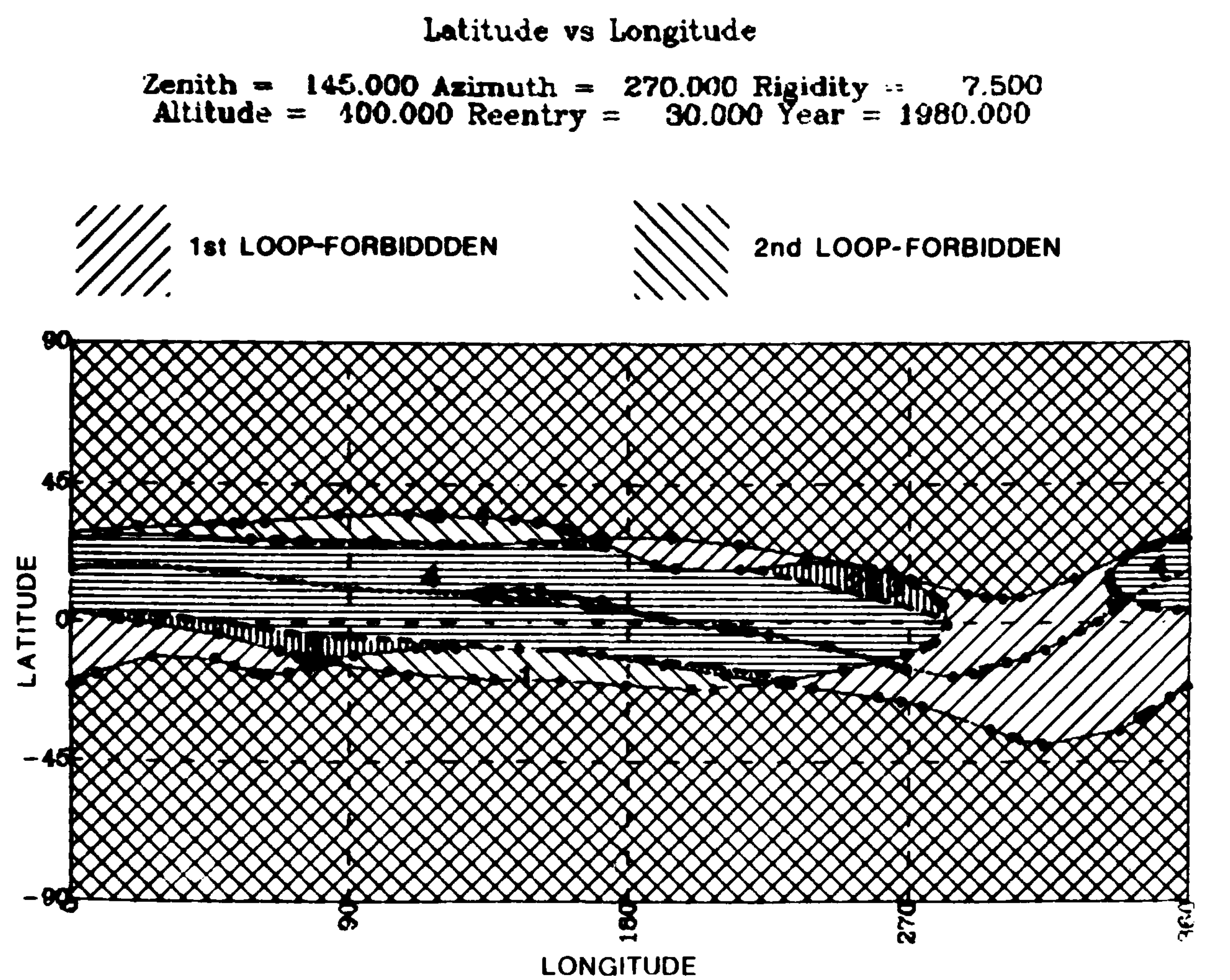

Figure 8. Latitude-longitude map for the conditions noted, showing categorized zones of access (this Figure corresponds to the same set of conditions under which Figure 6 was produced, except that it corresponds to 145° zenith rather than the 150° zenith of Figure 6).

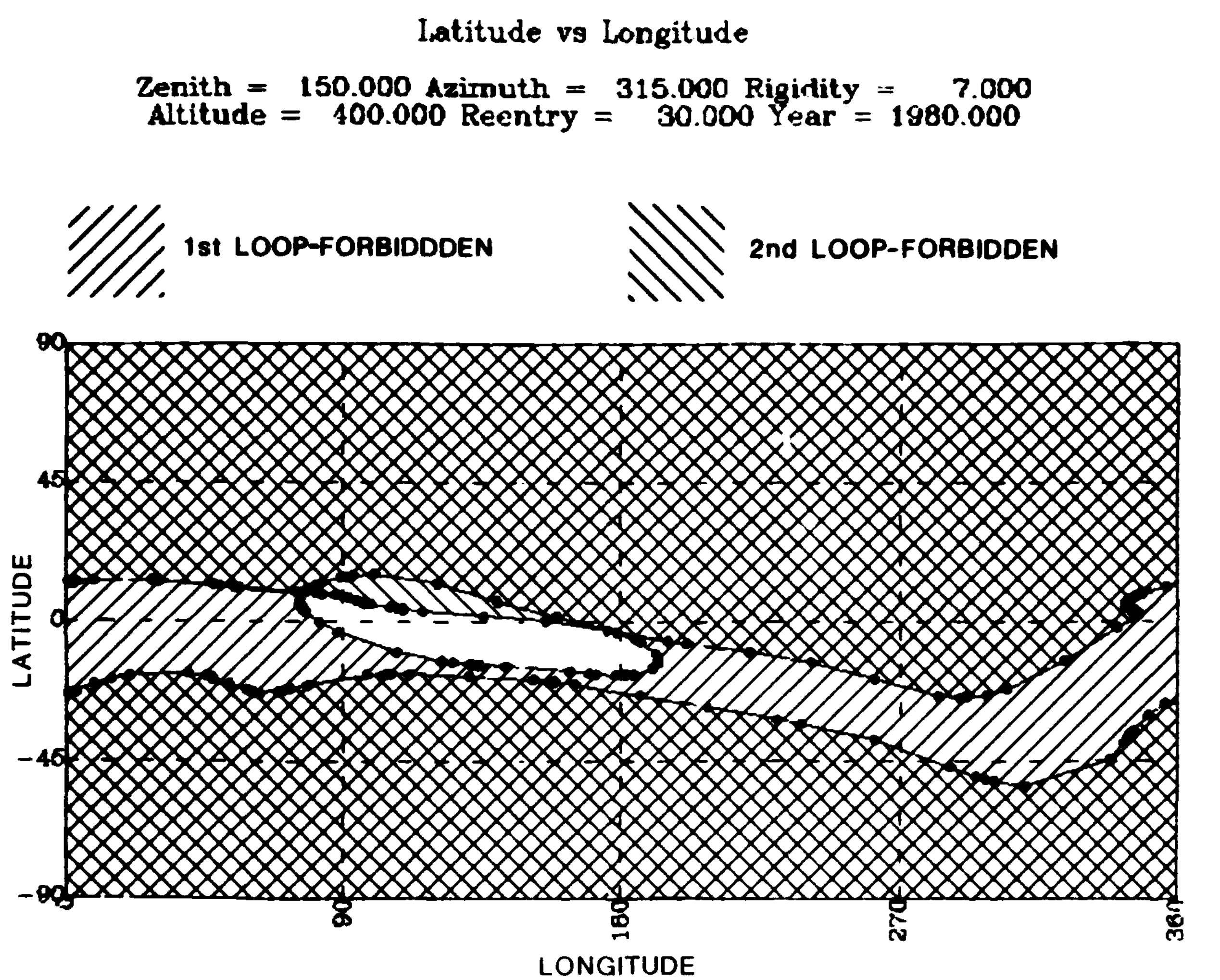

Figure 9. Latitude-longitude map drawn for same conditions as for Figure 6, except that azimuth is now 225°, rather than 270° east of north.

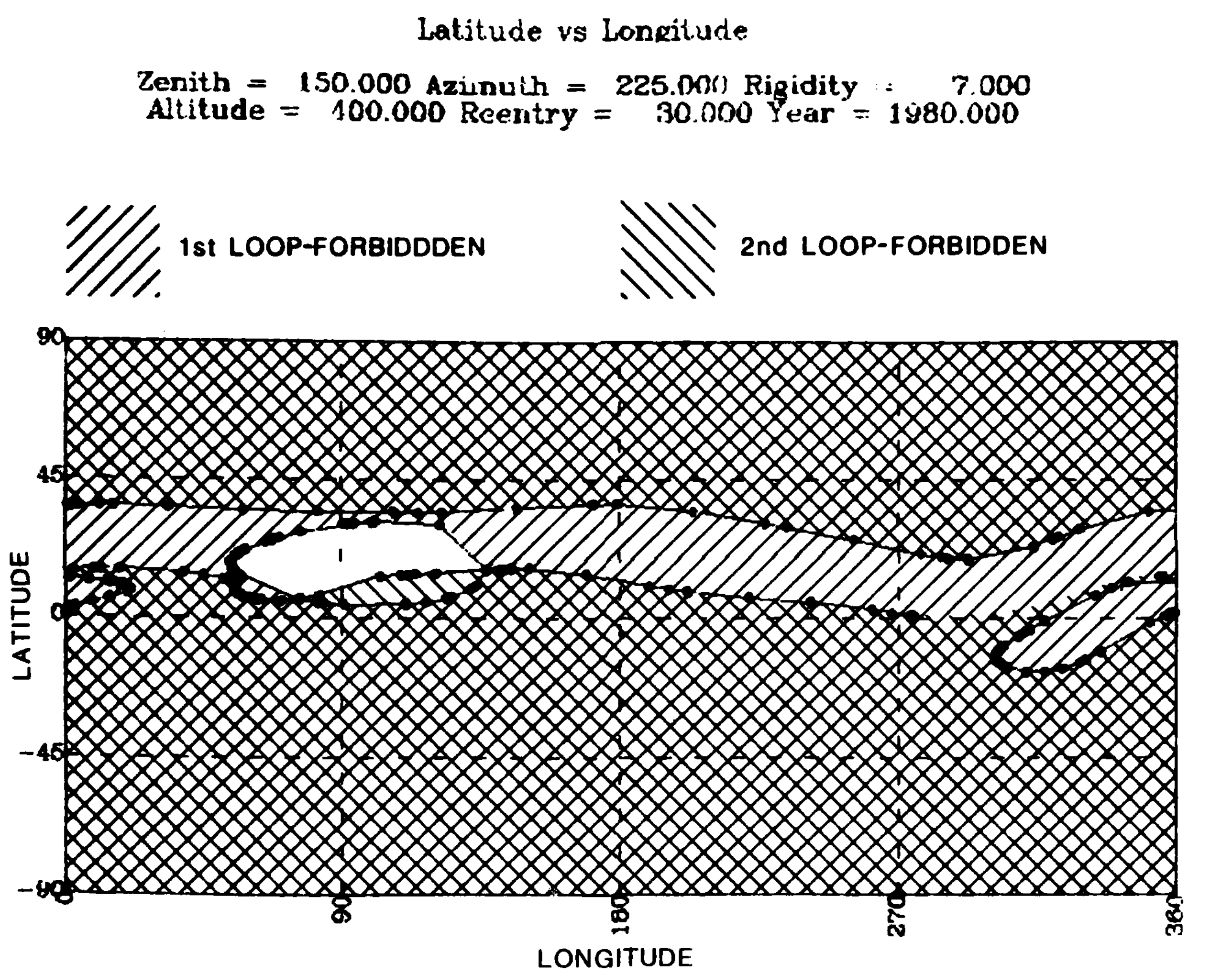

Figure 10. Latitude-longitude map drawn for same conditions as for Figure 6, except that azimuth is now 315°, rather than 270° east of north.

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